Geologic Resource Evaluation Scoping Summary
El Malpais National Monument, New Mexico

This summary highlights a geologic resource evaluation scoping session for El Malpais National Monument held in Grants, New Mexico, on March 30, 2006. The NPS Geologic Resources Division (GRD) organized this scoping session in conjunction with El Morro National Monument in order to view and discuss geologic resources, address the status of geologic maps and digitizing, and assess resource management issues and needs. Participants at the meeting included GRD staff, park staff, and cooperators from the New Mexico Bureau of Geology and Mineral Resources and Colorado State University (table 1). Prior to the meeting, on March 16, 2006, Ken Mabery (geologist and former management assistant at El Malpais National Monument), Bruce Heise (geologist, NPS Geologic Resources Division), and Katie KellerLynn (geologist/research associate, Colorado State University) participated in a conference call to gather pertinent background information about geologic resources of El Malpais and El Morro National Monuments; Mabery was not able to attend the scoping meeting on March 30 in New Mexico.

Table 1. Scoping Session Participants

Name	Affiliation	Phone	E-Mail
Tim Connors	NPS Geologic Resources Division (geologist)	303-969-2093	tim_connors@nps.gov
Kayci Cook Collins	El Malpais and El Morro National Monuments (superintendent)	505-285-4641	kayci_cook@nps.gov
Nelia Dunbar	New Mexico Bureau of Geology and Mineral Resources (geologist)	505-835-5783	nelia@nmt.edu
Bruce Heise	NPS Geologic Resources Division (geologist)	303-969-2017	Bruce_Heise@nps.gov
Katie KellerLynn	Colorado State University (geologist/research associate)	801-364-1716	katiekellerlynn@msn.com
Ron Kerbo	NPS Geologic Resources Division (cave specialist)	303-969-2097	ron_kerbo@nps.gov
Ken Mabery*	Fort Necessity National Battlefield and Friendship Hill National Historic Site (superintendent)—formerly with El Morro and El Malpais	724-329-5802	ken_mabery@nps.gov
Greer Price	New Mexico Bureau of Geology and Mineral Resources (geologist/chief editor)	505-835-5752	gprice@gis.nmt.edu
Peter Scholle	New Mexico Bureau of Geology and Mineral Resources (state geologist)	505-835-5294	scholle1@nmt.edu
Herschel Schulz	El Malpais and El Morro National Monuments (chief ranger)	505-285-4641, ext. 25	herschel_schulz@nps.gov

*Participated in March 16, 2006, conference call only.

Thursday, March 30, involved a welcome and introduction to the Geologic Resource Evaluation (GRE) Program, including the status of reports and map products. During the welcome, Kayci Cook Collins, superintendent for El Morro and El Malpais National Monuments who has studied geology, said “We’re glad you’re here. Rocks are our friends,” which got the session off to a good start. The morning’s discussion focused on map coverage of the monument and other “quadrangles of interest” in the vicinity of El Malpais. In addition, Bruce Heise facilitated a group discussion regarding the geologic processes and features at the monument. In the afternoon, attendees participated in a short field trip led by Nelia Dunbar and Herschel Schulz to view some of the resources at El Malpais, including the sandstone bluffs and the McCartys flow (3,800 years old), the youngest lava flow in New Mexico.

Overview of Geologic Resource Evaluation Program

Geologic features and processes serve as the foundation of park ecosystems and an understanding of geologic resources yields important information for park decision making. The National Park Service (NPS) Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. Ultimately, the inventory and monitoring of natural resources will become integral parts of park planning, operations and maintenance, visitor protection, and interpretation.

The Geologic Resource Evaluation (GRE) Program, which the NPS Geologic Resources Division administers, carries out the geologic component of the inventory. Staff associated with other programs within the Geologic Resources Division (e.g., abandoned mine land, cave, coastal, disturbed lands restoration, minerals management, and paleontology) provide expertise to the GRE effort. The goal of the GRE Program is to provide each of the identified "natural area" parks with a digital geologic map and a geologic resource evaluation report. In addition, the Inventory, Monitoring, and Evaluation Office of the Natural Resource Program Center is preparing a geologic bibliography for each of these parks. Each product is a tool to support the stewardship of park resources and is designed to be user friendly to non-geoscientists.

The scoping process includes a site visit with local experts, evaluation of the adequacy of existing geologic maps, and discussion of park-specific geologic management issues. Scoping will result in a summary (this document), which along with the digital geologic map, will serve as the starting point for the final GRE report. The emphasis of scoping is not to routinely initiate new geologic mapping projects but to aggregate existing information and identify where serious geologic data needs and issues exist in the National Park System. Scoping meetings are usually held for individual parks though some address an entire Vital Signs Monitoring Network.

Bedrock and surficial geologic maps and information provide the foundation for studies of groundwater, geomorphology, soils, and environmental hazards. Geologic maps describe the underlying physical framework of many natural systems and are an integral component of the physical inventories stipulated by the National Park Service in its Natural Resources Inventory and Monitoring Guideline (NPS-75) and the 1997 NPS Strategic Plan. The NPS geologic resource evaluation is a cooperative implementation of a systematic, comprehensive inventory of the geologic resources in National Park System units by the Geologic Resources Division; the Inventory, Monitoring, and Evaluation Office of the Natural Resource Program Center; the US Geological Survey; state geological surveys; and universities.

For additional information regarding the content of this summary, please consult the NPS Geologic Resources Division, located in Denver, Colorado. Up-to-date contact information is available on the GRE Web site at http://www2.nature.nps.gov/geology/inventory/.

The objectives of the geologic resource evaluation scoping meetings are as follows:

- To identify geologic mapping coverage and needs
- To identify distinctive geologic processes and features
- To identify resource management issues
- To identify potential monitoring and research needs

Outcomes of the scoping process include the following items:

- A scoping summary (this document)
- A digital geologic map
- A geologic resource evaluation report

Status of Scoping and Products

As of April 2006, the NPS Geologic Resources Division had completed the scoping process for 160 of 272 "natural resource" parks. Staff and partners of the GRE Program have completed digital maps for 68 parks. These compiled geologic maps are available for downloading from the NR-GIS Metadata and Data Store at http://science.nature.nps.gov/nrdata. The US Geological Survey, various state geological surveys, and investigators at academic institutions are in the process of preparing mapping products for 42 parks. Writers have completed 22 GRE reports with 18 additional reports to be completed by the end of fiscal year 2006.

Geologic Maps for El Malpais National Monument

During the scoping session on March 30, 2006, Tim Connors (GRD) presented a demonstration of some of the main features of the digital geologic map model used by the GRE Program. This model incorporates the standards of digitization set for the GRE Program. The model reproduces all aspects of a paper map, including notes, legend, and cross sections, with the added benefit of being GIS compatible. Staff digitizes maps using ESRI ArcView/ArcGIS format with shape files and other features, including a built-in help file system to identify map units.

Parks in Inventory and Monitoring Networks have identified "quadrangles of interest" mapped at one or more of the following scales: 7.5' × 7.5' (1:24,000), 15' × 15' (1:62,500), or 30' × 60' (1:100,000). Often for simplicity, geologic map makers compile maps at scale 1:100,000 (30' × 60'), which provides greater consistency and covers more area. However, for the purpose of geologic resource evaluations, GRE staff would like to obtain digital geologic maps of all identified 7.5-minute (1:24,000-scale) quadrangles of interest for a particular park. The geologic features mapped at this scale are equivalent to the width of a one-lane road.

Map coverage for El Malpais National Monument initially consisted of 24 quadrangles of interest (scale 1:24,000): Grants, Grants SE, San Rafael, Paxton Springs, Valle Largo, Los Pilares, Arrosa Ranch, Ice Caves, Cerro Hueco, Goat Hill, Laguna Honda, North Pasture, Ice Caves SE, Cerro Brilliante, Cerro Alto, Mecate Meadow, Cebollita Peak, Sand Canyon, York Ranch, La Rendija, Cerro Pomo, Wiley Mesa, Wild Horse Canyon, and Bonine Canyon. The Grants, Grants SE, and San Rafael quadrangles are situated on the Grants 30' × 60' sheet. The Paxton Springs and Valle Largo quadrangles are situated on the Zuni 30' × 60' sheet. The Los Pilares, Arrosa Ranch, Laguna Honda, North Pasture, Mecate Meadow, Cebollita Peak, Sand Canyon, Wiley Mesa, Wild Horse Canyon, and Bonine Canyon quadrangles are situated on the Acoma Pueblo 30' × 60' sheet. Ice Caves, Cerro Hueco, Goat Hill, Ice Caves SE, Cerro Brilliante, Cerro Alto, York Ranch, La Rendija, and Cerro Pomo are situated on the Fence Lake 30' × 60' sheet (see fig. 1). Park staff wants to add the McCartys quadrangle to this list. This quadrangle is located directly east of the Grants SE quadrangle and contains the important McCartys lava flow.

In 2003 GRE staff digitized *Geologic Map of El Malpais Lava Field and Surrounding Area, Cibola County, New Mexico* (GMAP 1076), and provided these data to park staff. (GMAP numbers, which appear throughout this document, are identification codes, part of the GRE database.) Though this map does not cover all quadrangles of interest, it suffices for resource management needs at El Malpais National Monument. Thus no further action is required for quadrangles not covered with one exception: park staff would like to have digitized data for the McCartys quadrangle, thereby incorporating the entire McCartys lava flow into the monument's GIS. This would help park staff gain a more complete understanding of the monument's geologic resources, in particular, how basaltic lava travels. The US Geological Survey published a preliminary map of the McCartys quadrangle in 1977. GRE staff will evaluate this map for possible digitization and conversion into the GRE model. This reference is as follows:

Maxwell, C.H., 1977, Preliminary geologic map of the McCartys quadrangle, Valencia County, New Mexico: US Geological Survey Open-File Report OF-77-380, scale 1:24,000 (GMAP 19127).

Other sources of information for the McCartys quadrangle include the following:

Nichols, R.L., 1946, McCartys basalt flow, Valencia County, New Mexico: Geological Society of America Bulletin, v. 57, no. 11, p. 1049, scale 1:422,000 (GMAP 56879).

Carden, J.R., and Laughlin, A.W., 1974, Petrochemical variations within the McCartys basalt flow, Valencia County, New Mexico: Geological Society of America Bulletin, v. 85, no. 9, p.1479, scale 1:370,000 scale (GMAP 57866).

McLemore, V.T., Broadhead, R.F., Roybal, G., Chenoweth, W.L., Barker, J.M., North, R.M., Bowie, M.R., Hingtgen, J.S., Murray, D., Klein, K., Brown, K.B., and Austin, G.S., 1986, Geologic map of Cibola County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 230, scale 1:50,000 (GMAP 73586).

Since publication of Maxwell (1977), more recent investigators (e.g., Tracy Cascadden and Joseph Andrew) have further divided the lava flows; this has added to the understanding of the geologic resources at El Malpais. For instance, papers in Mabery (1997) (see reference below) include specific divisions of the lava flows. Nelia Dunbar (New Mexico Bureau of Geology and Mineral Resources) is willing to compile information from the Mabery volume and other sources to be added to the monument's current geospatial database. In addition, Nelia tracked down and contacted Tracey Casscadden (now Graham) in the hopes of acquiring data that could be used to upgrade the digital maps of the recent flows at the El Malpais National Monument. However, the digital data that Tracey has are of the few things she got published (e.g., in Bulletin 156); she could probably find these files (contact: tracey_graham@sbcglobal.net). Nevertheless, these files may not be particularly useful because they were not produced on a topographic base.

Mabery, K., ed., 1997, Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources Bulletin 156, 185 p.

Cascadden, T.E., Geissman, J.W., Kudo, A.M., and Laughlin, A.W., 1997, El Calderon cinder cone and related basalt flows, *in* Mabery, K., ed., Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources Bulletin 156, p. 41–52.

Cascadden, T.E., Kudo, A.M., and Geissman, J.W., 1997, Discovering the relationships in a family of volcanoes—Cerro Candelaria, Twin Craters, Lost Woman Crater, and Lava Crater, *in* Mabery, K., ed., Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources Bulletin 156, p. 53–59.

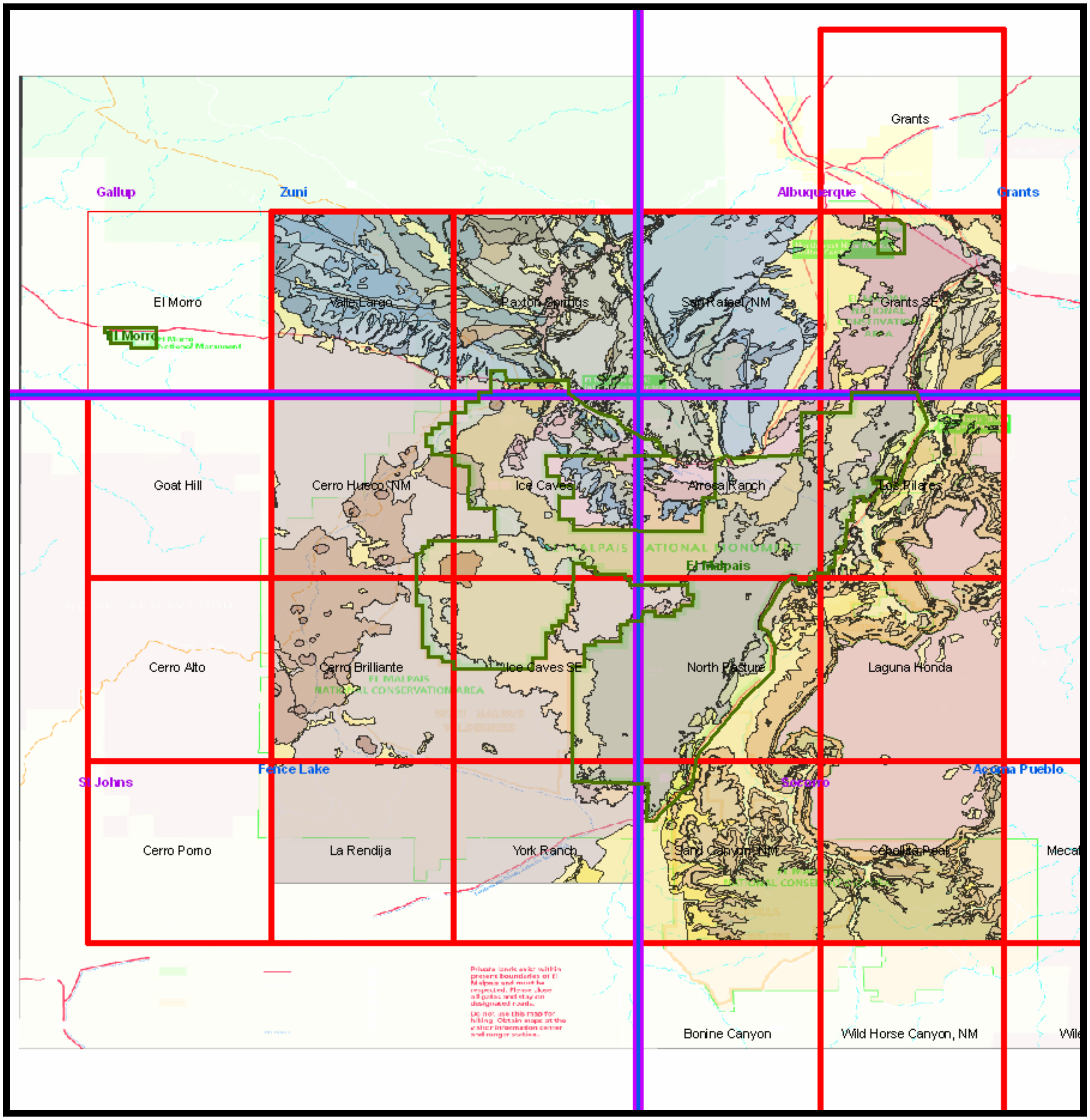

Figure 1. Quadrangles of interest for El Malpais National Monument, New Mexico. The 7.5-minute quadrangles (scale 1:24,000) are outlined in red with their names in black; names in blue indicate 30-minute by 60-minute quadrangles (scale 1:100,000). Green outline indicates the boundary of the monument. The McCartys quadrangle is not labeled on the figure but is located immediately east of the Grants SE quadrangle.

Geologic Overview

In part due to the presence of the Rio Grand Rift and Jemez lineament, many examples of volcanic and plutonic rocks occur in New Mexico. The Jemez lineament shows a striking alignment of relatively young volcanic features. The lineament is a zone of crustal weakness that may be tied to mantle activity. The volcanic rocks at El Malpais National Monument are part of the Zuni–Bandera volcanic field, which falls on the Jemez lineament.

The Zuni–Bandera volcanic field consists of Hawaiian-style volcanism with relatively low explosive features, the upper limit of which would have been fire fountains that reached nearly 1,000 feet (300 m) high. The Zuni–Bandera volcanic field contains eight eruptive events that have occurred in the past 50,000 years. The most recent explosive event, approximately 3,800 years ago, produced the youngest lava flow in El Malpais National Monument and New Mexico—the McCartys flow. The flow follows topography, and though it has a low gradient, it is quite long. This flow is beautifully preserved because of the arid conditions of the region. As such, many examples of volcanic features from El Malpais are included as part of the 2004 edition of *Lava Flows and Lava Tubes: What They Are, How They Form* produced by Ken Hon and volcanovideo.com. Being so accessible, the McCartys flow is very useful in public education.

Geologic Resource Evaluation Report

Geologic Resource Evaluation reports include sections about geologic resources of concern for management (referred to as "issues"), geologic features and processes, the park's geologic history, a map unit properties table that highlights the significant features and resource concerns for each map unit in the park, references (different from the bibliography), and various appendices (e.g., map graphics and scoping summary). This document (scoping summary) will serve as a starting point for information to be included in the final GRE report that will accompany the digital geologic map for El Malpais National Monument.

Geologic Features, Processes, and Issues at El Malpais National Monument

The scoping session and pre-meeting conference call for El Malpais National Monument provided the opportunity to capture a list of geologic features and processes operating in the monument. This summary includes information from both the conference call on March 16, 2006, and the scoping session on March 30, 2006. Some of these features and processes may be of management concern.

Cave Features and Processes

Investigators have inventoried the major lava tube systems in El Malpais National Monument. Research of the major lava tube systems is discussed in *Natural History of El Malpais*. By contrast, the secondary cave systems have not been extensively studied (e.g., Hoya Volcano). Most of what is known about the secondary systems has been interpreted during overflights, for example, during fires. Ken Mabery noted that he has seen a "collapse structure" from the air, which has not been thoroughly studied.

El Malpais National Monument has a memorandum or understanding with the Sandia Grotto, the local chapter of the National Speleological Society, for conducting basic inventory and cartography. Park managers have not completed a cave management plan, but Ron Kerbo could assist with this, initially by guiding staff through preparing a PMIS statement. Managers are directed to the intranet site at http://inside.nps.gov/waso/waso.cfm?prg=739&lv=4 (cave and karst page—including NPS cave management policy and guidance sections) and http://inside.nps.gov/waso/custommenu.cfm?lv=4&prg=739&id=2641 (cave management documents) for information and examples about how to prepare a plan. Park staff currently relies on the Federal Cave Resources Protection Act and Wilderness Act for making decisions regarding cave management and protection.

The monument's current database of information (electronic and hardcopy) contains cave descriptions and treats the various lava tubes as cave systems. Cave locations are tied into a GIS. The database contains recommendations for management and research, information about cultural materials found in the caves, public accessibility, ice in caves, and the locations of cave entrances. Five caves are currently open to the public; the other 250 identified caves require permits, which Herschel approves or denies after checking the database. New locations of caves are discovered during every inventory, for instance, an SCA intern found 30 new caves in 2001–2002. Hence, park staff needs help keeping the database up to date.

Generally speaking, park staff needs to evaluate current data-gathering practices, upgrading the system, and current cave-use policies. In particular, Ron Kerbo suggested reevaluating current uses of caves, including assessment of current needs for particular caves (e.g., interpretation of wildlife).

Ice caves

El Malpais contain every imaginable variety of ice caves: crystalline, stalactite and stalagmite, and "ice rink" (with frozen floors). Ice caves in El Malpais National Monument are among the southern most caves with ice in North America. The amount of ice in the caves varies from year to year. The ice caves in the monument are similar to those at Lava Beds National Monument in California and Craters of the Moon National Monument in Idaho, though El Malpais easily surpasses Craters of the Moon in variety. The lava tubes at

The layers of ice within the ice caves record climate change and response. Investigators have dated the layers, similar to the rings of trees, which show past chronology of wet and dry years. In addition, unique assemblages of lichens and mosses grow at the mouths of caves. The cave microclimate is similar to arctic climates, where these plant assemblages typically grow. Also, ferns, similar to those that grow in the Pacific Northwest, grow at the mouths of caves and in collapse structures. Interesting fauna includes microorganisms that form "cave crusts," as described in Northup and Welbourn (1997), and spiders. Also, Lightfoot (1997) describes several new species of crickets from some of the monument's more remote caves.

Northrup, D., and Welbourn, W.C., 1997, Life in the twilight zone—Lave-tube ecology, *in* Mabery, K., ed., Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources Bulletin 156, p. 69–82.

Lightfoot, D.C., 1997, The fauna of El Malpais, *in* Mabery, K., ed., Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources Bulletin 156, p.139–154.

Resource management issues surrounding the ice caves include water quality (see discussion regarding truncated streams in "Streams (Fluvial) Feature and Processes" section) and degradation of cave resources.

Volcanic Features in Caves

The caves at El Malpais were a significant part of the insulation and transport of lava on the Zuni–Bandera volcanic field. Braiding (e.g., Braided Cave) is the result of transport of lava in the volcanic field. Various features exemplify insulation and thermal erosion in the caves, such as lava high-tide marks, lava stalactites, and bell-shaped profiles. The monument's lava tubes contain features that are primary to cave formation, called speleogens, such lavacicles and helictites. Post-formation "secondary features" called speleothems are the result of the interaction of water in the cave environment; at El Malpais they include mineralization of calcite, gypsum, and mirabilite. Collapse structures are also indicative of the lava tubes at El Malpais.

Stream (Fluvial) Features and Processes

On the west side of the monument Agua Fria Creek, an ephemeral stream, flows after flooding from snowmelt upstream. This flooding causes some concern for infrastructure because prior landowners have diverted the channel through the parking lot at El Calderon. The stream channel originally flowed directly behind the fire cache and information center. Flooding events occurred in 1987 and 1999.

Fluvial processes are a factor of general erosion on the east side of the park, particularly between the sandstone bluffs and the McCartys flow, which affects an area with highly concentrated archaeological sites. In addition, the highway on the east side periodically gets washed out.

Streams only flow after flash-flooding events. One important aspect of the stream channels is that they become truncated under the lava flows. This feature is significant for resource management because of the potential degradation in water quality within the monument's cave (lava tube) systems. Streamflow originates outside the monument but flows into the monument's lava tube systems, introducing potential contaminants and changing cave ecology. Source areas of potential contamination are in the northwest corner and southeast side of the monument. In the northwest corner near Bandera Crater, pesticides and grazing occurs on small adjacent ranches and other private lands. The southeast side of the monument near Highway 117 has the greatest potential for contamination, primarily because of grazing on Pueblo and BLM lands.

Junction Cave in the El Calderon area is the only lava tube known to respond to surface-water flow; it flows with water after flash floods. The lava tubes at El Calderon become a natural storm drain system. In general, surface water percolates into the groundwater system within a few weeks after a flash flood. Windmills attest to past extraction of groundwater for livestock use. Park staff has eliminated windmills from monument land; however, some wells have been retained for their historical value and use by wildlife.

Lake (Lacustrine) Features and Processes
Interglacial lake sediments (i.e., Trace Hermonos Formation) were deposited east of what is now El Malpais National Monument. These gravelly sediments, which occur within the national conservation area, are equivalent with other Lake Bonneville sediments. Active lacustrine features include swampy areas in the low areas on the lava flows. Nichols (1946) was the first to describe these features:

Nichols, R.L., 1946, McCartys basalt flow, Valencia County, New Mexico: Geological Society of America Bulletin, v. 57, no. 11, p.1049–1086

More recent research describes vegetation associated with wet areas on the lava flows:

Bleakly, D.L., 1997, Plant life on the lava—The vegetation and flora of El Malpais, *in* Mabery, K., ed., Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources Bulletin 156, p. 113–138.

In addition, natural potholes called tinajas occur in the sandstones units, with smaller ones occurring on the lava flows. They are a significant source of surface water in the monument, though one—Laguna Juan Garcia—may have a natural (groundwater) seep. Tinajas form over time through fluvial processes that scour out the bedrock. They are typically an ephemeral or episodic source of water for wildlife. Humans have also created earthen stock tanks for watering livestock; some of these may have cultural significance as they were carved in the 1200s or 1300s. Another lacustrine feature at the monument is small playas that develop along the edges of the lava flows.

Volcanic Features and Processes
Volcanism at El Malpais National Monument is generally attributed to activity along the Rio Grande Rift. The recurrent interval of volcanism over the past 50,000 years—the best-dated interval of volcanism in the Zuni–Bandera volcanic field—has been approximately 5,000 years. Volcanic activity at El Malpais spanned two million years, with the older end of the spectrum being less well dated. The Acoma and Zuni peoples have volcanic stories as part of their cultures, for example, one story describes a volcano being the home of a monster whose children poked out its eyes. El Malpais has volcanic features galore.

Natural History of El Malpais documents many of the features with excellent photos. The lava fields are very rugged, with a three-mile trip taking nearly all day in some areas.

Research of the monument's volcanic setting and features is ongoing. For example, Nelia Dunbar (New Mexico Bureau of Geology and Mineral Resources) is currently reviewing a paper for the Geological Society of America publication, *Geology*, about the geochronology of the Blue Water flow in El Malpais. In general, integration of more recent volcanic data into the monument's GIS would aid resource management. Nelia Dunbar volunteered to assist with identifying these data.

According to Ken Mabery, geologic data used by park managers at El Malpais contain a few "holes." First, the area around Lost Woman Crater in the northwestern portion of the monument deserves attention. Original mapping (from aerial photographs) missed features in this volcanic field because it is heavily forested. Only Tracy Cascadden has looked at this area and then only briefly; Mabery conducted some reconnaissance on the ground, which revealed a previously unidentified cinder cone vent.

Second, the Bandera flow requires further research to understand its "story." This flow is huge (approximately 23 miles [37 km] long) and composed of aa, which contrasts with other pahoehoe events (e.g., Hoya) in the monument.

Third, unanswered research questions still remain regarding the monument's youngest volcanic event, represented by the McCartys flow. The chemical analysis of this flow is not widely different from other flows in the monument; however, it is the longest flow at El Malpais and extruded from a small vent. Hence, questions remain about why this flow was so fluid. Maxwell mapped this flow as a single homogeneous unit but a curiosity is why the aa flows occurred in a "sea" of pahoehoe. In addition, Maxwell mapped surface faults on the McCartys flow, but more recent research has not revealed any such features. These surface faults may line up as a series of spatter cones; the inference being extrusion along a fault. However, this idea has not been field verified.

Geologists group the volcanic features at El Malpais National Monument into three main categories: flows, vents, and lava tubes (caves). Flow margins are well exposed in the monument (e.g., at Lava Falls) and the relative geochronology is well defined. Flows consist of pahoehoe and aa. Pahoehoe produces ropey flow tops. Multiple ropes occur at different scale. Pahoehoe flows can expand as more lava collects under a solid crust. Other features of pahoehoe flows at El Malpais include the following:

- Fissures
- Squeeze ups
- Inflation features
- Surface collapse
- Pressure ridges
- Surface tube systems
- Vesicle stratigraphy (bubbles migrated up through lava—an indicator of flow tops in bedrock)

Aa flows move like bulldozers, creating rubbly, clinkerly, or spiney tops. Other features of aa flows include rafting of lava within flows, and a more viscous composition than pahoehoe, thereby trapping air bubbles. Lava flows may contain both pahoehoe and aa, changing as a result of gradient or a later pulse of different viscosity lava.

Different plants selectively grow on different flows, for instance, pygmy pines grow on the McCartys flow, and aspen and Douglas fir grows on older flows. *Cinders phacelia* grows only on cinders. The lava flows also affect animal species. Melantropic lizards that live on the lava have a darker color than those that live off the flows. Six or eight types of crickets are unique to the flows. Biologists discovered a new species of cricket, not yet described, on one of the flows.

The primary type of vent at El Malpais is cinder cones. The shape of the cinder cones, typically asymmetrical, is controlled by wind direction. Therefore, cinder cones are indicators of paleowinds. Bedding (layers) shows how cones built over time. The lifespan of an active cone is generally between one and 50 years. Cone morphology changes through time via erosion. The alignment of the cinder cones is along a zone of crustal weakness. Breaches in the cones fed flows. Rootless vents (i.e., hornitos and spatter cones) also occur in the monument.

Shields, another type of vent, also occur in the vicinity of the monument. The characteristic feature of shields is shape, which as the name implies resembles a shield, that is, a flattened dome. Shields form by progressive, very fluid pahoehoe lava on low slope gradients. Cerro Rendija is a good example of a shield at El Malpais.

The third main category of volcanic features at El Malpais is lava tubes (caves). Rivers of lava in the tubes flowed under hardened crusts. When the lava was flowing, spectators could have seen it through skylights, like in Hawaii today. The Zuni–Bandera volcanic field has many lava tubes and collapse structures (see “Cave Features and Processes” section).

Windblown (Eolian) Features and Processes

Sand dunes occur along the eastern side of the monument, along the fringes of monument, and coming in from older flows from the west and south. The friable Zuni sandstone is the primary source of eolian sediments in the monument. Kipukas (usually lava but any “paleo high” of older material) are another source. The North Pasture Ridges, a significant Cretaceous outcrop of Zuni sandstone at El Malpais, consists of a complex of upturned bluffs, south of the Narrows Picnic Area. During BLM management, cattle heavily grazed this area, which may have contributed to windblown erosion. In addition to grazing, other agricultural practices in Grants, New Mexico, known as the “carrot capital of the world,” contribute to eolian features, including significant dust storms. Moreover, the North Pasture Ridges area is likely to experience future development, which could create new source areas of eolian sediments, as well as affect water quality.

Erosion of the sandstone bluffs influences the lava flows by providing materials that assist in the “aging process.” Infilling of voids with loess is the first stage in eventual soil development on the lava flows. Eolian dunes also encroach upon and override portions of the flows.

Maxwell’s mapping is straightforward for the bluffs. By contrast, Maxwell’s map does not show any significant eolian features (e.g., dunes), though they appear on aerial photographs.

Seismic Features and Processes

The intact nature of the lava flows indicates that seismic activity has not occurred recently. The most recent “felt quake” was in the 1970s. However, earth cracks exist south of Point of Malpais in the BLM conservation area, which may be an indicator of seismic activity in the region.

Unique Geologic Features

Xenoliths

Some of the lava tubes in the monument contain xenoliths (e.g., Junction Cave and Lava Crater). Researchers use xenoliths for dating bedrock and past volcanic activity, for example, in the necks of volcanoes. Most of the xenoliths are fully encapsulated and found in cave walls; however, some may have originated at the surface as sandstone blocks (from the bluffs and narrows), which fell into lava flows.

Xenoliths provide clues to bedrock under the lava flows and help determine the erosive history of the valleys under the flows at the present-day surface.

Paleontological and Archaeological Resources

The most noteworthy paleontological resources at El Malpais National Monument are tree molds, for example, those on the surface of the McCartys and Bandera flows. Investigators have just begun to document these resources; they have identified three localities with a total of 15 or 20 tree molds on the Bandera flow.

In addition, limestone kipukas may contain fossils, though no one has researched this. In addition to many archaeological artifacts, the caves contain other paleontological resources including Quaternary pack rat middens and animal remains. Ken Mabery mentioned bighorn sheep remains within Braided Cave; all that is known about the age of these remains is that they predate the 1950s (Herschel Schulz, El Malpais and El Morro National Monuments, written communication, April 20, 2006).

Geologic Age Points

Investigators have extensively studied many of the lava flows at El Malpais; for example, Andrew (1997) describes age points for many of the flows. In general, university researchers continue to be interested in using the monument as a field area to test dating methods, in particular "cross dating" techniques (e.g., sulfur and carbon-14). Nelia Dunbar mentioned that cosmogenic techniques are particularly useful for dating flows of the Zuni–Bandera volcanic field (Dunbar and Phillips, 2004). Laughlin and others (1993) records a list of age dates of the nine most recent flows in the monument.

Andrew, J., 1997, Volcanic history of the northern chain of craters, *in* Mabery, K., ed., Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources Bulletin 156, p. 31–40.

Laughlin, W.A., Charles, R.W., Reid, K., and White, C., 1993, Field-trip guide to the geochronology of El Malpais National Monument and the Zuni–Bandera volcanic field, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 149, 24 p.

Dunbar, N., and Phillips, F., 2004, Cosmogenic ^{36}Cl ages of lava flows in the Zuni–Bandera volcanic field, north-central New Mexico, USA, *in* Cather, S.M., McIntosh, W.C., and Kelley, S.A., eds., Tectonics, geochronology, and volcanism in the Southern Rocky Mountains and Rio Grande Rift: New Mexico Bureau of Mines and Mineral Resources Bulletin 160, p. 51–59.

Disturbed Lands

A national monument was proposed for the El Malpais region beginning in the 1930s; however, the uranium boom during the 1950s postponed establishment until 1987. Past legacies of land use consist of 80% Bureau of Land Management, 15% USDA Forest Service, and 5% private. The two main issues for park managers regarding disturbed lands are (1) a highly visible cinders quarry in the northwest corner of the monument near Bandera Crater and (2) an abandoned cinders quarry on the side of El Calderon crater. In addition, a sandstone quarry in the Lava Falls area has been reclaimed and is no longer an issue. The State of New Mexico used sandstone blocks from the sandstone quarry for culvert headwalls. Park staff revegetated the area in 1996 with the goal of restoring and naturalizing the drainage at this site.

The inholder of the Bandera cinders quarry sells gravel to the state highway department for use as road base. The quarry is privately owned and still active; the owner has cooperated with the National Park Service in the past. Because this disturbed site is adjacent to NPS land, it appears to the public to be a "park problem." The El Calderon quarry site is owned by the NPS and is no longer being used. This mine site is difficult to reclaim because recontouring cinders is a challenge. Park staff is considering simply leaving the site in its present state and interpreting the area as a historic mine site.

Other disturbed lands include heavily grazed areas. The area surrounding the monument consists of a checkerboard of past and present grazed lands. Grazing ceased after 1997 in the monument; the enabling legislation allowed 10 years for grazing to cease. Staff continues to survey and fence park lands with NRPP funding. Most areas other than the lava fields have been overgrazed. A number of kipukas (older lava islands surrounded by younger lava flows, ranging in size from a few feet to ½ mile long × ¼ mile wide) were only slightly or not grazed, so natural vegetative assemblages remain intact. Past sheep grazing was a “transient” Navajo activity, though more recent cattle grazing is the primary concern for park management. One significant point for management of the kipukas is that these features (e.g., Hidden Kipuka) host remnant vegetation, for example, the southern most extent of alligator juniper.

Logging activities in the 1970s caused disturbance in what is now El Malpais National Monument. In areas not subject to logging, the lava flows host the oldest living Douglas fir and juniper, for example, “Yoda tree.” Park management is protecting some of the sawmill sites as cultural resources. Logs and slash cut during logging are now being removed during prescribed burns. Old logging roads in wilderness area are now closed to motorized vehicles; however, park managers do not plan to restore these roads.

Geologic Interpretation and Education

Presently, staffing allows for an interpretive presence at visitor centers, with some outreach to local schools, though not regularly. The National Park Service helps staff a multi-agency center in Grants—the Northwest New Mexico Visitor Center—and an information center on Highway 53 on the way to El Morro National Monument.